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THE OPTICAL SYSTEM OF THE NACA 400,000-FRAME-PER-SECOND MOTION-PICTURE CAMERA

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SUMMARY

The optical principle of the NACA ultrahigh-speed camera is explained. This camera has been operated in the NACA laboratories at the rate of 400,000 frames (photographs) per second, and speeds up to 1,000,000 or more frames per second are anticipated. The camera has been used in the study of knock in the reciprocating spark-ignition engine.

Simplified sketches are included illustrating the optical principle and main design features of the camera, but without minor design details. The inherent aberrations of the optical system are discussed. Photographs of the camera are presented. A sample of photographs of the phenomenon of knock taken with the camera at 200,000 frames per second is included to illustrate the quality of the work done with the camera.

INTRODUCTION

The NACA ultrahigh-speed camera has been developed during the period 1939-47 for use in the study of knock in the reciprocating spark-ignition engine. The camera is based on an optical principle invented early in 1939. The basic principle of operation is described in reference 1. The ultrahigh-speed camera has been successfully operated at rates as high as 400,000 frames (photographs) per second and is expected to operate eventually at 1,000,000 or more frames per second.

Before the development of the ultrahigh-speed camera, the NACA had used a camera operating at the rate of 40,000 frames per second in the knock studies (reference 2). Although the photographs taken at 40,000 frames per second revealed much new information concerning knock, the need of a higher speed to reveal all details of knock was apparent early in 1939.

Contrary to the experience with the camera of reference 2, great difficulty was encountered in successful operation of the ultrahigh-speed camera. The difficulty never involved the optical principle of the camera, but rather the mechanical details. The camera is now in routine operation at 400,000 frames per second, however, and is being limited to that speed in order that an extensive set of photographs of the knock phenomenon may be obtained before the camera is subjected to the slightly greater risks involved in the higher speeds.

The new camera is of the optical-compensator type, in the sense that the photographic image is rapidly moved from one part of the film to another while optical elements compensate, during the actual exposure time of an individual image, for the relative motion between image and film. The optical system has one basic point in common with the optical system described in reference 2 but is so different in details that the two systems appear superficially to be entirely dissimilar.

A large number of optical-compensating devices are known, and one or another is used in any case where the picture-taking rate is so high that the film cannot be moved intermittently (except with spark photography). In all these devices, compromises must be made between various desirable but conflicting characteristics. The device described herein is probably capable of attaining a higher mechanical speed than any other optical compensator known to this author. In exchange for the high mechanical speed, the camera design requires some sacrifice in optical speed and quality of definition, and also does not allow the projection of the photographs as a motion picture without a frame-by-frame reprinting process. The sacrifice in quality of definition is important only when the scale of the moving objects to be studied is marginally small. Even with marginal size of moving objects to be studied, an increase in picture-taking rate can readily be shown to compensate exactly for a proportional increase in diameter of the circle of confusion. Increase in picture-taking rate makes possible the use of a telephoto lens as objective, with proportional increase of magnification ratio on the photosensitive film. The increased picture-taking rate compensates for the increased speeds of motion resulting from the greater magnification ratio. Furthermore, lost definition can be at least partly regained by a further decrease in optical speed. In the study of knock, the quality of definition and the optical speed of the new camera have been sufficient to realize the full benefit of the increased mechanical speed up to 400,000 frames per second.

The principle of operation of the new camera is fully explained herein. The illustrative sketches, however, are simplified to reveal only the main design features without going into minor design details.

Acknowledgment is made to Alois Krsek, Jr., for valuable suggestions which made possible a material reduction in number of lenses required in the camera as well as some improvement in definition. A mechanical shutter to control over-all operating time of the camera was devised by Newell D. Sanders and a later electronic light control for the same purpose was developed by Gordon E. Osterstrom with some contributions from the author. All of these men are members of the Cleveland laboratory staff.

This discussion will be concerned primarily with the optical features of the camera and will not go into details of the motive power for the rotating part of the camera. During the first few years of development, the motive power was supplied by an air turbine developed at the University of Virginia (reference 3). During the past 3 years, however, the air-turbine drive has been abandoned and an electromagnetic suspension and drive have been developed for the camera rotor. The electromagnetic system was based on a similar development at the University of Virginia (reference 4), but with some novel features. The electromagnetic system has been developed primarily by Theodore Male, with some contributions by Thomas A. Dallas, Richard P. Krebs, and the author, all of the NACA technical staff.

BASIC PRINCIPLE OF OPTICAL SYSTEM

The ultrahigh-speed camera is of the optical-compensator type. The photosensitive film is entirely stationary, and rotating mirrors with a system of stationary lenses produce a succession of stationary images at different positions on the film. The camera is similar to the camera described in reference 2 only in the fact that both cameras form primary images at positions far from the photosensitive film and perform mechanical operations on the light beams at the positions where the primary images are formed. The elementary principle of the new camera is illustrated in figure 1 in a form designed to take a series of only two successive photographs.

The optical elements in figure 1 are a rotating plane mirror, a stationary condensing lens, and a stationary objective lens arranged with two pairs of stationary refocusing lenses on an arc of an imaginary circle having the rotating mirror as a center. The stationary photosensitive film is arranged along the arc of another circle, of larger diameter, also with the rotating mirror as a center.

The objective lens in figure 1 is focused to produce a stationary primary image of the photographic object on the surface of the rotating mirror. The condensing lens, whose function will be described later, is located so close to the rotating mirror and to the stationary primary image that it has little effect on the formation of the primary image or on the secondary images formed by the refocusing lenses on the photosensitive film.

Because the primary image is formed on the surface of the rotating mirror, the beam of light reflected by the rotating mirror revolves about the primary image as a center. The reflected beam revolves, of course, with an angular velocity twice as great as the angular velocity of the mirror itself. When the reflected beam in its rotation passes over refocusing lens pair 1, this lens pair forms stationary secondary image 1 on the photosensitive film at the position indicated in the figure. At this time no light is passing through refocusing lens pair 2, except a small amount caused by diffuse reflection from the rotating mirror and by flare from the other lenses; consequently refocusing lens pair 2 forms no appreciable secondary image. A little later, however, after the mirror has rotated through one-half the angular displacement between the two pairs of refocusing lenses, the reflected light beam passes through refocusing lens pair 2. Stationary secondary image 2 is then formed on the photosensitive film at the position indicated in the figure, but secondary image 1 is then dark.

The fundamental function of a lens is to focus all rays of light coming from any given point at one conjugate focus to a corresponding point at the other conjugate focus, regardless of the direction in which the rays leave the given point at the first conjugate focus. As the primary image formed on the rotating mirror is stationary and is located at the first conjugate focus of the refocusing lens pairs 1 and 2, the secondary images formed on the photosensitive film at the second conjugate focuses of refocusing lens pairs 1 and 2 are also stationary, regardless of the rotation of the reflected beam about the primary image as a center. The rotation of the reflected beam constitutes only a change in direction of the light rays leaving any particular point in the primary image and, according to the fundamental function of a lens, all the rays must go to the same point in the secondary image regardless of the change of direction of the rays. (The discussion in this paragraph applies only to the question of translational motion of the secondary images as a whole. The rotation of the reflected beam does introduce aberrations that are discussed in the section Disadvantages and Aberrations.)

The function of the condensing lens shown in figure 1 is to cause all, or nearly all, the light from the objective lens to go through one of the refocusing lens pairs at the same time. The condensing lens is placed with its rear side toward the objective lens and refocusing lenses and with its principal focus on the arc of the circle on which the objective and refocusing lenses are arranged. With this arrangement, an image of the objective lens is formed in the reflected light beam on the circular arc. As this image of the objective lens is located at the same distance from the condensing lens as is the objective lens itself, the image of the objective lens has the same size as the objective lens. If, however, the image of the objective lens has the same size as the objective lens, then the cross section of the reflected light beam at the point where the image of the objective lens is formed must have the same size and shape as the objective lens. The refocusing lenses have the same diameters as the objective lens and therefore with this arrangement, the cross section of the reflected beam is just right to allow all the beam to pass through one of the refocusing lens pairs at one time.

If only one pair of refocusing lenses were used in figure 1, the camera would be simply a "still" camera with an extremely high-speed shutter, and for some purposes such a shutter in a still camera might have some advantages. With the two pairs of refocusing lenses, as shown in figure 1, the system is equivalent to two still cameras with high-speed shutters timed to go off at slightly different times.

DESIGN FEATURES

Optical Arrangement Used In Practice

Obviously more than two pairs of refocusing lenses can be used in the arrangement shown in figure 1 - in fact, as many pairs of refocusing lenses can be used as may be crowded into the usable circular arc about the primary image as a center - and a secondary image may be formed by each pair of refocusing lenses in succession.

In order to obtain the greatest possible number of refocusing-lens pairs, the circular arc upon which these lenses are arranged must be extended throughout a greater angle than is permissible with a condensing lens of reasonable proportions. This difficulty is eliminated in practice by dispensing with the condensing lens and grinding the rotating mirror with a concave spherical surface instead of a plane surface. If the spherical mirror surface is ground with its center of curvature at a point on the same circular arc on which the objective lens and refocusing lenses are arranged, this mirror surface performs the combined functions of the rotating plane mirror and the condensing lens shown in figure 1. The usable circular arc can then be extended considerably more than 90° to each side of the objective lens. (Refocusing lenses are shown in fig. 1 on only one side of the objective lens; they can, however, be placed on both sides.) With large angles of incidence of the light beam on the rotating concave mirror, the image of the objective lens formed in the reflected beam is not good; the poor quality of this image, however, has only slight effect on the quantity of light transmitted through a refocusing lens at one time.

In the placing of refocusing lenses on each side of the objective lens, a difficulty arises in that no refocusing lens can be placed in the same position as the objective lens. Consequently, if the refocusing lenses are placed as closely together as possible, the succession of refocusing lenses must be broken at the time the reflected light beam passes over the objective lens. This difficulty can be overcome by raising or lowering the reflected beam to a different level from that of the incident beam. If the axis of the incident beam lies in a horizontal plane, with the axis of rotation of the concave mirror vertical, and if the mirror is ground with its center of curvature on a higher or lower level than the plane of the incident beam, then the reflected beam extends out above or below the plane of the incident beam and passes over or under the objective lens without interference as it rotates. Such an arrangement, furthermore, allows the use of a rotor with a number of concave mirror surfaces reflecting beams on different levels as shown in figures 2 and 3.

The ultrahigh-speed camera is shown in figures 2(a) and 2(b) as used in practice, except that mechanical details are greatly simplified. Figure 2(a) is a horizontal section through the central plane of the camera and figure 2(b) is a vertical section, also through a central plane. The rotor has six concave spherical reflecting surfaces; each surface throws the reflected light beams successively through each of 15 lenses on one of six different levels. In figure 2(a) the apertures for the 15 lenses may be seen on each of three levels below the plane of the paper. The other three levels are above the plane of the paper. In figure 2(b) all six levels of refocusing-lens apertures may be seen, but seven of the lenses on each level are above the plane of the paper and are not shown.

The photosensitive film, as shown in figures 2(a) and 2(b), is arranged in 15 vertical strips instead of six horizontal strips. Arrangement in horizontal strips would require that each film strip be cut in such a manner that when laid down on a flat surface the strip would form an approximately circular arc. This peculiar and inconvenient manner of cutting would be necessary in order that the center lines of the strips would conform approximately with horizontal planes when fitted to the inner surface of the film-holding sphere. With the arrangement of the film in 15 vertical strips ordinary roll film (but specially cut 7/8 in. wide) can be used with sufficiently accurate fit about the spherical film-holding surface.

In the present design of the camera, the over-all picture-taking time must be limited to the interval required for one complete revolution of the camera rotor. This limitation is provided by timing a flash of light to last only for this interval of time. The light source is a battery of xenon-filled flash tubes through which a bank of condensers is discharged. The ordinary uncontrolled discharge of a condenser through a flash tube allows such a gradual decay of the light radiation as to be quite unsuitable for the purpose. In order to avoid the gradual decay, a sufficient condenser capacity is used to maintain practically constant light intensity for the entire time interval desired. At the end of this time interval, an electronic timing circuit causes the xenon-filled flash tubes to be short-circuited by a grid-controlled arc tube. The short-circuiting of the flash tubes causes the light decay to take place within only a few microseconds.

In the actual ultrahigh-speed camera four objective lenses are used, instead of one as in figure 1, for reasons that will be explained. These four objective lenses are all visible in the section of figure 2(a), and the apertures for two of these objective lenses may be seen in figure 2(b); the apertures for the other two objective lenses are above the plane of the paper in figure 2(b). Light enters the camera through the "master aperture" shown in figure 2(b) and is reflected by the four 45° mirrors shown in figure 2(a) through the four objective lenses to the camera rotor. Only one of the 45° mirrors is shown in figure 2(b).

With only one objective lens, whole photographs could not be taken continuously for one complete rotation of the camera rotor, with the arrangement otherwise as shown in figures 2(a) and 2(b), because the primary image would be split by the camera rotor whenever the intersection of two adjacent rotor faces passed over the primary image. At such times the light falling on one of the rotor faces would be reflected out through one pair of refocusing lenses at the same time that the light from another rotor face was being reflected through another pair of refocusing lenses. Two partial secondary images would be formed, one on one of the 15 film strips, another on another of the film strips. The two partial images could be fitted together to form a complete image, but an arrangement that would form whole images at all times was preferred.

A continuous, uniformly timed series of whole images for a complete revolution of the rotor can be obtained with two objective lenses forming two primary images on the reflecting faces of the rotor such as the upper two images or the lower two images shown in figure 3. The two images must be of the proper size and must be positioned in such a manner that both images will fall on a single rotor face at the same time when the face is in the correct position (figs. 2(a) and 3). If the two objective lenses are arranged with an angular spacing equal to an exact multiple of the angular spacing between two adjacent pairs of refocusing lenses (the multiple is 3 in the actual camera), then the two reflected light beams leaving the rotor from the positions of the two primary images will pass through different pairs of refocusing lenses at the same time so long as the two primary images are falling on the same rotor face. With this arrangement, at all times when a rotor-face intersection is passing over one of the primary images the other primary image is falling full on a rotor face and whole secondary images are being formed corresponding to the primary image that is falling full on a rotor face. Whole secondary images are consequently formed on one film strip or another throughout the entire period of rotation of the rotor.

Four objective lenses, and four primary images, are actually used in the camera in order to double the number of pictures taken during a single revolution of the camera rotor and to double the picture-taking rate. Because of mechanical considerations, a space had to be left between adjacent refocusing-lens pairs nearly as great as the diameter of a lens. With only two objective lenses, therefore, the camera would be blind during the time that the reflected beams were falling on spaces between adjacent refocusing lenses. With two pairs of objective lenses, offset from each other by an amount equal to $1\frac{1}{2}$ times the angular spacing between adjacent refocusing-lens pairs, photographs can be taken with one of the two pairs of objective lenses while the other pair is blind. A series of 102 consecutive photographs is taken during one complete turn of the rotor by each of the two lens pairs. The two series of 102 photographs alternate chronologically throughout so that they can be interspersed to form one uniformly timed series of 204 photographs.

When all four primary images are falling full on a single rotor face, and sometimes when two of the primary images are falling full on one rotor face and the other two primary images are falling full on an adjacent rotor face, two whole secondary images are exposed at the same time. In such cases the better of the two images is selected for use and the other is discarded. The result is that 24 full images are used on the central one of the 15 vertical film strips, 18 images are used on each of the 4 film strips closest to the central film strip (2 on each side of the central strip), 12 images are used on each of the 8 film strips next farther out (4 on each side of the central strips), and 6 images are used on each of the two outermost film strips - 204 images in all.

The positions of the 90 pairs of refocusing lenses and the four objective lenses are shown in figure 4 as they appear on the developed surface of the spherical wall of the rotor chamber in which they are mounted. As shown in the figure, the refocusing lenses do not form straight horizontal rows nor do they form straight vertical rows except in the central position. The four objective lenses, on the other hand, are arranged in a straight horizontal row in the central position.

The refocusing lenses are not arranged in straight horizontal rows because the reflected light beams in their rotation about the primary images do not maintain a constant angle with the central horizontal plane. Instead, each rotating reflected beam rises to a maximum level when it is directly over (or under) the objective lens from which it originally came, and drops to a lower level as it rotates to either side of that position. The refocusing lenses are not arranged in straight vertical rows because the reflected beams that are deflected farthest from the central horizontal plane have greater angular velocities in their projections on the central horizontal plane than do the reflected beams that are less deflected from the central plane. The arrangement of the lenses in vertical rows that are progressively more curved from the center outward is necessary in order that the same picture-taking frequency will obtain for one bank of 15 lenses as for another bank.

All of the refocusing lenses except the outermost six on each side in figure 4 form more than one secondary image that is actually utilized. In all cases one of the images, formed by one of the four reflected beams, calls for a slightly different position of the refoucusing lens than does any of the other images formed by some other one of the four reflected beams. If the refocusing lens is not placed at the proper elevation for one of the reflected beams, then only part of the light from that beam passes through the lens; if the refocusing lens is not located properly from side to side, then the photograph is not taken at quite the right time. The lens positions shown in figure 4, however, represent a very satisfactory compromise between the requirements of the four different reflected beams.

Camera Dimensions

The camera rotor measures approximately $1\frac{1}{8}$ inchs through from the center of one reflecting face to the center of the opposite reflecting face. The length of the off-axis prismatic rotor, measured along the prismatic axis, is about $1\frac{1}{16}$ inches. The rotor in the original turbine-driven model had only a short cylindrical extension at top and bottom, off axis as referred to the hexagonal prism, about 1/2 inch in diameter and 3/8 inch long. The cylindrical extensions at both ends were used in the mounting of the rotor during machining and in the balancing of the rotor. In the actual spinning of the rotor, however, only the lower cylindrical extension was used for mounting and the upper extension was unrestrained. In the later electromagnetic suspension and drive, the rotor has been provided with a much larger cylindrical extension above to act as an armature and a somewhat larger cylindrical extension below for control purposes.

The radius of curvature for the concave spherical reflecting surfaces on the rotor is $5\frac{1}{4}$ inches. The focal lengths of both inner and outer refocusing lenses are $5\frac{1}{4}$ inches, and both refocusing lenses and objective lenses have 1/2-inch diameters. The inner refocusing lenses are arranged at the surface of a sphere of $5\frac{1}{4}$-inch radius whose center is located 9/16 inch away from the axis of rotation of the rotor. The inner refocusing lenses are separated from the outer refocusing lenses about 7/8 inch. The film strips are arranged about the surface of a sphere whose radius is $11\frac{3}{8}$ inches, with the same center as the $5\frac{1}{4}$-inch sphere on which the inner refocusing lenses are arranged. Instead of being mounted inside an actual metallic sphere as shown in figures 2 and 3, the film strips are actually mounted in individual curved holders conforming to the surface of an imaginary sphere.

The film strips are 7/8 inch wide. This width is sufficient to allow for the fact that on the outer strips the images formed by the refocusing lenses on the central levels are not in the same horizontal positions as the images formed by the refocusing lenses on the upper and lower levels.

The four primary images formed on the rotor are each 1/4 inch in diameter; the secondary images formed on the film strips have the same size. The images could, of course, be made smaller at will, but they cannot be made larger if whole images are to be formed throughout the entire series of 204 frames.

Rotor Drive and Camera Operation

The first motive power used for the camera rotor was an air turbine. The rotor was mounted on a piano-wire shaft, 0.039 inch in diameter, and spun like a top with shaft below but no shaft above.

The balancing of the rotor for operation with the air turbine was a difficult problem and will not be discussed in detail herein. The rotor, as shown in figures 2 and 3, has the appearance of being mounted off axis and therefore presumably out of balance. The rotor, however, is approximately a regular hexagonal prism. The ellipsoid of inertia of a prism with a regular polygon cross section is a spheroid whose axis coincides with the axis of the prism. Furthermore, the length of the camera rotor is almost exactly right to make the inertial spheroid actually a true sphere. The rotor is therefore approximately in balance about any axis that passes through the center of gravity of the prismatic portion and may be mounted off the axis of the prism. The balancing of the near-spherical body, however, is difficult. As the shape of a rotating body is changed to approach the spherical condition, the critical speeds associated with dynamic unbalance become greater and, as the critical speeds become greater, the necessary degree of dynamic balance to pass safely through the critical speeds increases. Theoretically, as the rotor approaches the spherical condition the critical speeds associated with dynamic unbalance become great without limit and failure of the shaft at a critical speed may be positively assured even with infinitesimal unbalance. In order to pass through a critical speed successfully or to operate above the critical speed, the true axis of the spheroid of inertia must coincide with the shaft axis within the allowable limit of angular deflection. Consequently, the true axis of the spheroid of inertia must be located and made to coincide with the axis of the rotor shaft. When the rotor approaches the spherical condition very closely (but never actually reaching it in practice), the true axis of the inertial spheroid may be extremely difficult to determine.

The rotor used in the camera, (figs. 2 and 3), does not actually have its ends cut perpendicular to the prismatic axis. The difference from perpendicularity is sufficient to move the axis of the inertial spheroid entirely around to the position of the shaft axis, even though the difference is not perceptible to the eye.

With the rotor used in the camera, approximately $1\frac{1}{8}$ inches across flats, and with the 0.039-inch-diameter shaft, the critical speed at which shaft failure most often occurred was about 1200 rps. Before the rotor could be spun through this critical speed consistently, 3 years of experimentation on mounting and balancing of the rotor were required. Consistent spinning of the rotor at 5500 rps, corresponding to a picture-taking rate of 1,122,000 frames per second, was finally accomplished. The camera could not be operated at this speed, however. The air-turbine drive had to be abandoned because it was never possible to avoid the flinging and spattering of oil that came through the babbitt journal bearing. The high vacuum maintained in the camera chamber promoted the spattering. Although only a very small amount of oil came through the bearing, this oil crept up the shaft onto the rotor and was flung off onto the 94 lenses in the wall of the chamber in spite of numerous labyrinths and sealing devices that were tried.

One photographic shot of the phenomenon of knock was obtained with the air-turbine drive operating at 1000 rps, or with a picture-taking rate of 204,000 frames per second. Even at this rate, the 94 lenses in the chamber wall became fogged too badly for continued use after only six shots, five of which were not timed correctly to catch the knock phenomenon.

After the air-turbine drive was abandoned, about 3 years were devoted to the development of an electromagnetic suspension and drive for the rotor. This development, which eliminates all need for lubrication by substituting a magnetic bearing for the babbitt journal bearing, has been successful and the camera is now in operation with the electromagnetic suspension and drive at 400,000 frames per second.

Photographic Views Of Camera

A photograph of the assembled camera taken from the right front is presented in figure 5. Just below the inch scale may be seen the aluminum housing for the magnetic-suspension and drive coils for the camera rotor. A number of electrical connections extend from the aluminum housing to the electronic cabinet, a small portion of which is visible at the right of the figure. Immediately below the aluminum housing appears the black-painted semicylindrical evacuated chamber in which the camera rotor is suspended. The hemispherical portion of the evacuated chamber is inside the camera toward the rear and cannot be seen in this view.

The 2-inch pipe screwed into the upper part of the semicylindrical chamber connects this chamber, through a right-angle turn and a bellows, to a high-capacity diffusion pump, the upper part of which may be seen in the right foreground. Just below the 2-inch pipe, a 3/4-inch flange projects forward from the semicylindrical chamber. This flange, originally intended for mounting, marks the central horizontal plane of the chamber. The optical portion of the camera rotor is located within the chamber on the same level as this flange.

Beneath the semicylindrical chamber are leveling screws, base plate, and supporting stand with electrical outlets.

Above the inch scale appears a black crackle-finished light box, which provides the flash of light for taking pictures, and through which the light from the photographic object enters the camera. The heavy cable leading from the front of the light box to the side of the electronic cabinet supplies the condenser discharge to a battery of five xenon-filled flash tubes located inside the light box.

About 2 inches above the large cable connection at the front of the light box may be seen a large rectangular aperture, and on a higher level somewhat farther back another rectangular aperture. The light from the battery of xenon-filled flash tubes issues from the lower of these rectangular apertures and, when returning from the photographic object, reenters the light box through the upper aperture. The light then passes to the rear of the light box and is there reflected downward into the camera proper through the master aperture shown in figure 2(b).

In the left of figure 5 the edge of the housing for the film holders is seen as a large light-gray rectangle, and a small portion of the housing for the film rolls, the black crackle-finished portion at the extreme lower left of the camera, is also seen.

The housings for the film holders and film rolls may be seen more completely in figure 6, which was exposed from the right rear of the camera. These housings are approximately 120° sectors of two concentric cylinders; the taller inner cylinder is the housing for the film holders, and the low, flat outer cylinder at the bottom of the camera is the housing for the film rolls. In the central part of the film-holder housing may be seen a small sliding cover for a window, which is used for focusing. At the top of the light box in figure 6 may be seen four sets of screws for adjusting four mirrors that reflect light down through the master aperture into the camera proper.

The cover is removed from the film-holder housing in figure 7, which is otherwise the same as figure 6. Removal of the cover allows a view of the extreme upper ends of 15 film holders, with a strip of film extending out of the upper end of each holder. After a photographic sequence is exposed, about 1 foot of film is drawn out from the top of each holder and cut or torn off. The cover to the film-holder housing is then replaced and the camera is ready for another shot.

The film-holder housing and the film-roll housing, which are welded together to form an integral unit, have been removed from the camera and laid down in the foreground in figure 8. In this figure the 15 curved film holders, conforming to the surface of a sphere, may be clearly seen. Fifteen rolls of film in the film-roll housing, each 100 feet long, are threaded through velvet-edged slits in the lower part of the film-holder housing and hence through the velvet-lined film holders from bottom to top. In figure 8, slightly above the center of the central film holder, may be seen a rectangular aperture provided for focusing. This aperture conforms in position with the previously mentioned window in the film-holder housing.

In figure 9, five of the film holders have been removed from the camera. The velvet-surfaced cover strips have also been removed from three of the film holders. A film holder and a cover strip may be seen lying on the inner surface of the film-holder housing to the left of the inch scale. The six apertures through which photographs are exposed in each of the film holders may be seen where the cover strips have been removed. Some of the lenses in the hemispherical wall of the evacuated chamber may be seen through the open space made by removal of the five film holders. Black paper tubes have been provided, extending from each lens to the corresponding aperture in a film holder. Some of these paper tubes may be seen in place and one of them that has been removed from the camera is lying on the inner surface of the film-holder housing. On the central level of each of the three uncovered film holders may be seen a small stencil. A flashlight bulb, mounted in a small housing inside each film holder, is flashed once for each photographic shot to mark each film strip with a number, 1 to 15, through the stencils. The sockets for several of the flashlight bulbs may be seen in the space made by removal of the five film holders.

The 90 refocusing lenses in the hemispherical wall of the evacuated chamber are shown in figure 10, in which all the film holders are removed. The 15 sockets for the film-marking flashlight bulbs may be seen. On the central level of the hemispherical chamber wall may be seen the outer surface of a bracket that supports four front-surface mirrors. By means of these mirrors, the four light beams that come down through the master aperture at the top of the camera are reflected through four objective lenses into the evacuated chamber and onto the camera rotor. Four sets of five screws may be seen at the outer surface of the mirror-holding bracket; these screws provide the necessary adjustments for the mirrors.

Figure 11 is like figure 10, except that the bracket with its four mirrors has been removed from the hemispherical chamber wall and laid at the bottom of the camera just to the left of the inch scale. The four objective lenses in the hemispherical chamber wall may now be seen.

A camera rotor of the type used with the electromagnetic suspension and drive is shown in figure 12.

Disadvantages and Aberrations

The camera has a number of disadvantages that are a necessary result of the extreme high speed for which it was designed. Some of these disadvantages are listed and discussed:

1. The photographs taken with the camera cannot be projected as a motion picture just as they come from the camera, but must be carefully and painstakingly reprinted. In the simplest form of the camera (fig. 1) with only one objective lens and with the refocusing lenses arranged in the same plane with the objective lens, the lenses could be matched and located accurately enough that the series of secondary images would appear in proper position for projection as a motion picture on one circular strip of film. Such an arrangement, however, would greatly reduce the length of the series of pictures that could be taken in one shot with the camera. The sacrifice of projectability of the pictures appeared to be necessary in order to get a series of pictures of the length desired and at the speed desired. As the camera was actually constructed, the images are scattered over the different film strips in a very complex order; their positions horizontally and vertically are very irregular; different images are rotated as much as 90° relative to each other, and the images are not all of the same size. In order to project the photographs as a motion picture, a special projection printer, designed and constructed by Carl Louis Gregory of the National Archives, permits individual adjustment of the position of an image vertically and horizontally, the orientation of the image rotationally, and the magnification of the image.

2. The primary image formed on the camera rotor by an objective lens is in a plane perpendicular to the axis of that objective lens. When this primary image is viewed by the light of the reflected beam, the image has the appearance of being perpendicular to the axis of the reflected beam. As seen by the light of the reflected beam, the primary image therefore has the appearance of rotating about a line in its own plane with the same angular velocity as that of the axis of the reflected beam. Consequently, during the time of exposure of a secondary image, only those parts of the primary image that are located on the axis of the image rotation appear stationary. The other parts of the primary image move out and in from that axis; but worse, in the secondary image all parts of the image except the axis of rotation move in and out of focus because of the apparent rotation of the primary image about the line in its own plane. The motion even of the outermost parts of the image out and in from the axis of image rotation is entirely negligible. The blurring of some parts of the secondary image caused by the motion of those parts in and out of focus, however,

amounts to about 0.5 percent of the image diameter at the extreme ends of the exposure. The effect is less serious than it might seem because the intensity of the exposure gradually increases from and diminishes to zero at the beginning and end of the exposure; for most of the exposure the diameter of the circle of confusion caused by this effect is considerably less than 0.5 percent of the image diameter.

3. The four primary images formed by the four stationary objective lenses must each be focused in one fixed plane. Because the primary images are formed on different reflecting surfaces at different times, and on different parts of the different reflecting surfaces at different times, and because the different reflecting surfaces are ground on different angles relative to the axis of rotation, the primary images cannot be focused exactly on the reflecting surfaces except for a few of the exposures. In the cases where the primary images do not fall exactly on the reflecting surfaces, an apparent translational motion is imparted to the primary images during the exposure of the individual secondary images. This apparent translational motion of the primary image causes a smearing of the secondary image as exposed on the film. This aberration is by far the most serious. In extreme cases, this aberration moves portions of the secondary image almost 10 percent of the image diameter during the exposure. Here again the effect is less serious than it might seem because the exposure intensity gradually approaches zero at the beginning and the end of exposure.

4. Because the reflecting surfaces reflect the light beams out at an angle to the horizontal plane, they produce an apparent rotation of the primary image about the axis of the reflected beam during the exposure of an individual secondary image. This effect produces a rotational smear of the exposed image. From a practical standpoint, however, this rotational smear is only a measure of the variation of the aberration discussed in paragraph 3 between one part of an image and another. As the magnitude mentioned for the aberration in paragraph 3 is the maximum that occurs, the rotational smear does not need to be added but in fact amounts to a palliation of the aberration of paragraph 3.

5. The motion of the reflecting surfaces on the camera rotor is not rotational alone but includes a translational component. Part of the translational motion is in a direction parallel to the plane of the reflecting surface and is of no consequence, but in many cases a primary image falls on a part of a reflecting surface that has a very considerable translational velocity perpendicualr to the plane of the reflecting surface. This translational velocity of the reflecting surface causes the corresponding secondary image on the film to go in and out of focus during the process of exposure.

In some cases this aberration causes a circle of confusion somewhat greater than 0.5 percent of the image diameter at the beginning and the end of exposure. This aberration and the aberration of paragraph 2 may be treated together, in which case the primary image may be regarded as rotating about a line in its own plane but a line that does not pass through the image itself.

6. In cases where a single refocusing-lens pair forms two, three, or four secondary images that are utilized, these secondary images do not all come into sharp focus with the same positions of the refocusing lenses because these different secondary images are formed with the rotor in different angular positons. This aberration could be eliminated by the refractive effect of small flat plates of transparent material placed against the photosensitive film on the emulsion side, with a different thickness of plate for each secondary image. This aberration is so small, however, compared with some of the other aberrations that correction has not appeared worth while.

SAMPLE OF PHOTOGRAPHS TAKEN WITH ULTRAHIGH-SPEED CAMERA

Seven selected frames (not consecutive) from a photographic series of the phenomenon of knock in a spark-ignition engine taken with the ultrahigh-speed camera at the rate of 200,000 frames per second are shown in figure 13. Twenty consecutive frames of this same photographic series formed the basis of a study of spark-ignition engine knock reported in reference 5. The first two frames shown in figure 13 were exposed before the knock started to develop. In each of these frames about one-half of the combustion chamber is seen in a view looking almost straight down on the top of the piston. The combustion started at a spark plug located at the extreme left of the chamber, the side that was outside the field of view. Before the exposure of the first two frames of the figure, the flame traveled all the way across the field of view from left to right, and at the times of exposure of these two frames the flame was in the position indicated by the black cloud at the right side of each frame. The light gray mottled area in the left of each frame represents the gases in which combustion was complete.

The pictures show the burning zone as black and the burned regions as light gray, the reverse of what would normally be expected, because the pictures were taken by externally supplied light projected into the combustion chamber through glass windows. This light, after passing through the gases in the combustion chamber, was reflected from a mirror on the piston top back through the combustion-chamber contents and out of the glass window to the camera. The burning gases scatter the transmitted light to such an extent that it does not get through to the camera. The burned gases, however, allow the transmitted light to pass through in approximately straight lines, allowing it to reach the objective lenses of the camera. The light radiated by the burning gases was not sufficient to photograph at 200,000 frames per second.

The time interval between exposures of frames 1 and 2 was 20 microseconds, whereas the interval between frames 2 and 3 was only 5 microseconds. The start of the knock development, which is a detonation wave, is first visible in frame 3 as a whitening of a portion of the black burning zone in the location shown by the two white arrows. Although the time interval between frames 1 and 2 was four times as long as the interval between frames 2 and 3, the change in the appearance of the combustion zone between frames 2 and 3 is greater than the change between frames 1 and 2. The normal burning process that precedes the occurrence of knock is so slow in comparison with the knock phenomenon that the pictures taken at 200,000 frames per second show practically no change in the space of four frames with the normal burning, but show very marked change between two successive frames after the knock begins to develop.

In frames 4 and 5 of figure 13, taken 5 and 15 microseconds, respectively, after the third frame, the knock reaction eats into the black burning zone very rapidly and also produces a dark gray (not black) coloration in a part of the burned gases. Frame 6, exposed 20 microseconds later than frame 5, shows a number of small black spots explained as conglomerations of free carbon released by the knocking detonation wave. These conglomerations of free carbon, being opaque to the transmitted light, show up as black spots in spite of the fact that they are intensely incandescent. Their incandescence is no match for the transmitted light by which the pictures were taken and because of the extremely high picture-taking rate the incandescence is not sufficient to photograph.

In the last frame of figure 13, exposed 25 microseconds later than frame 6, the conglomerations of carbon particles have been drawn out into streaks in the direction of gas motion. Apparently the physical inertia of the carbon particles acted in some manner to draw them out into streaks as the expanding gases rushed by at tremendous speed.

CONCLUDING REMARKS

After several years of delay caused by technical difficulties, the ultrahigh-speed camera has been put into successful operation at the rate of 400,000 frames per second with good prospects of much higher speeds without further difficulty. Such speeds cannot be obtained without sacrifices and the sacrifice in definition has been great. In spite of the poor definition, however, the camera has served its purpose of providing definite confirmation of the detonation-wave character of knock. In any future redesign of the camera, no effort should be spared to bring the six different lens levels more closely together in order to reduce aberrations or to introduce any possible fundamental changes in the design to reduce aberrations. Appreciably better definition could probably be secured in the present design of the camera by use of objective and image lenses of higher quality.

Flight Propulsion Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, June 10, 1947.

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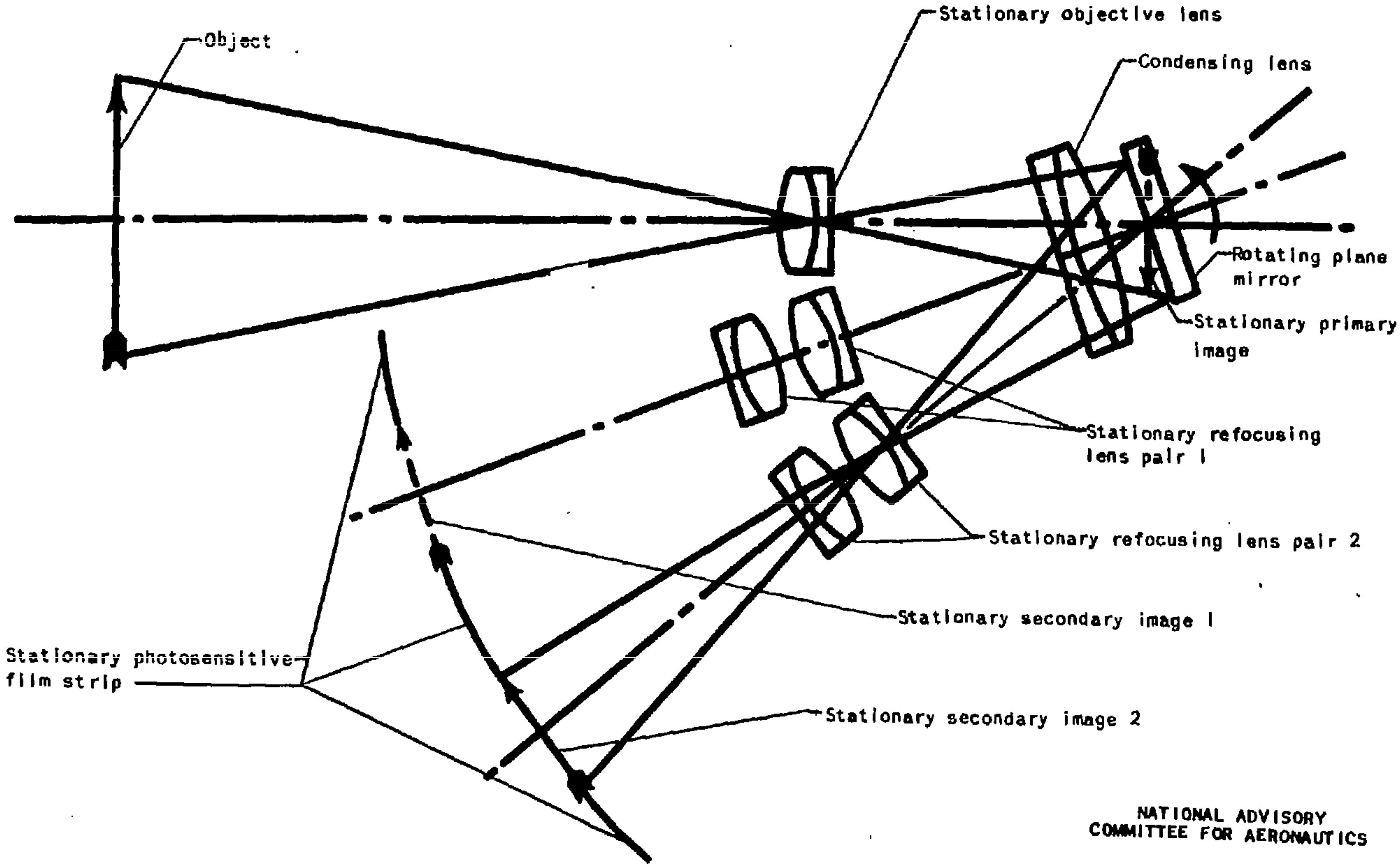

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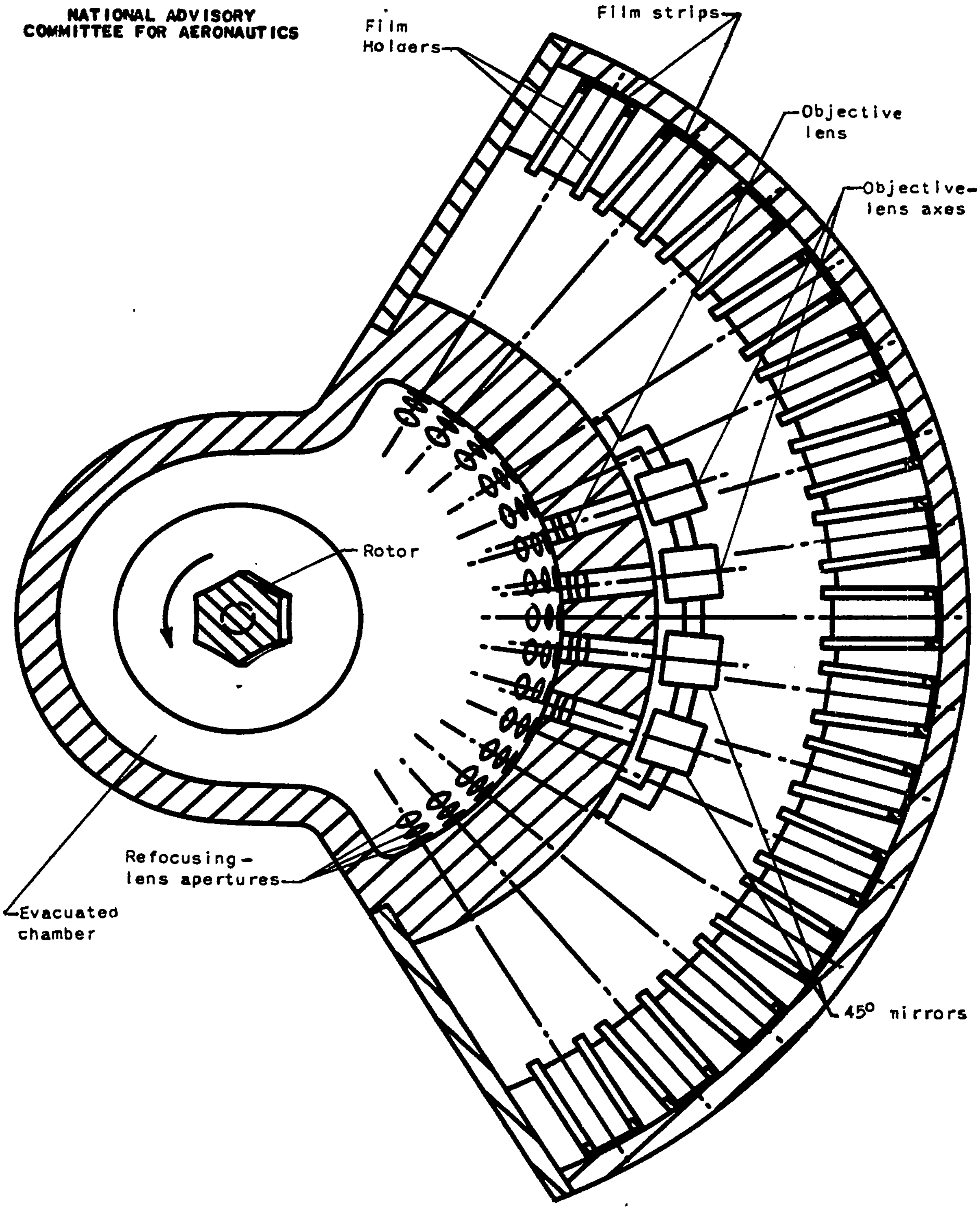
Figure 1.- Elementary principle of operation of ultrahigh-speed camera.



(a) Horizontal section.

Figure 2.-Schematic diagram of ultrahigh-speed camera.

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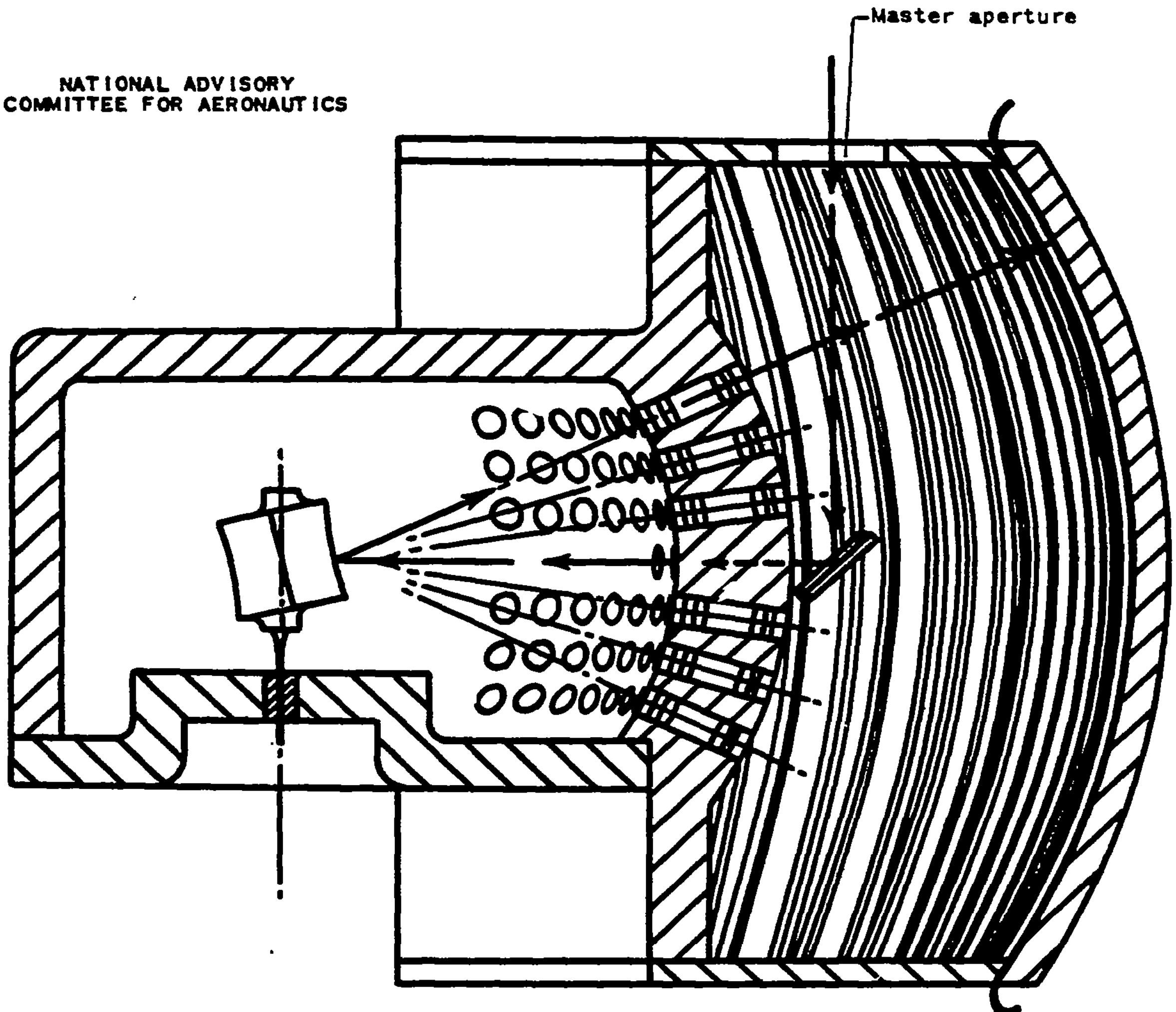

(b) Vertical section.

Figure 2.- Concluded. Schematic diagram of ultrahigh-speed camera.

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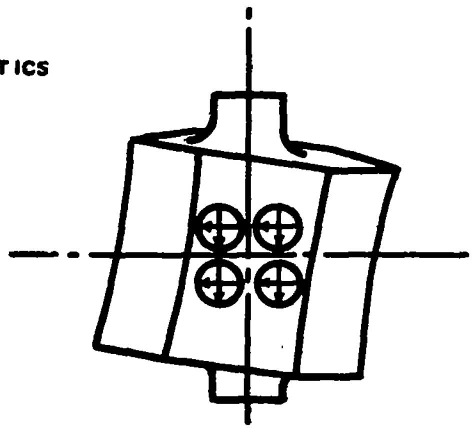

Figure 3.- Positions of four stationary primary images relative to rotor surface at one instant during rotation of rotor.

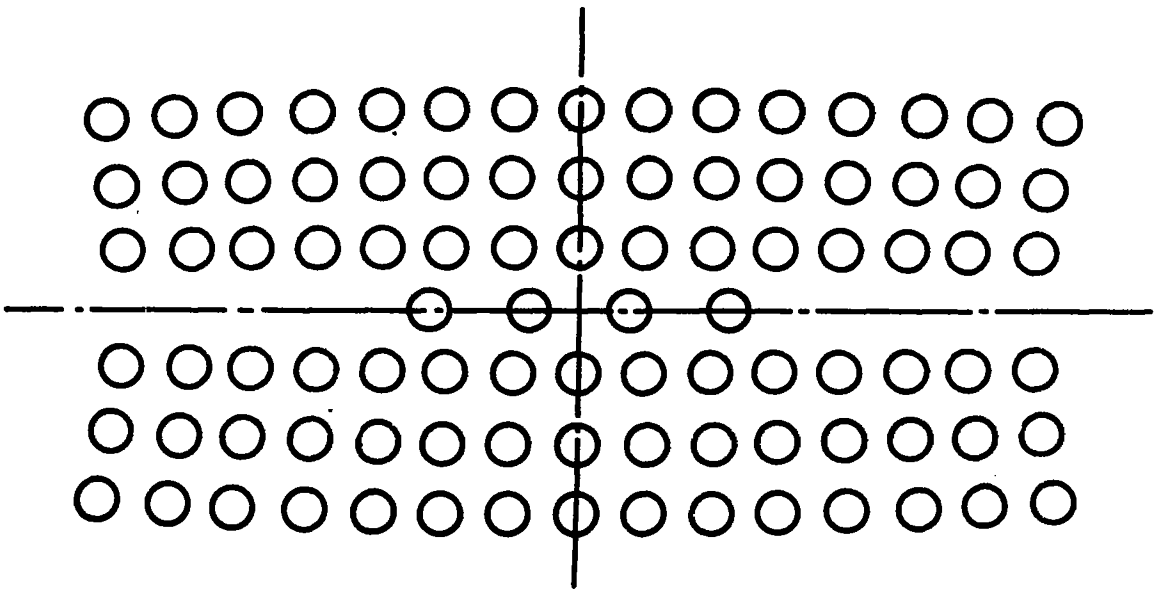

Figure 4.- Relative positions of objective lenses and refocusing lenses on developed surface of spherical chamber wall.

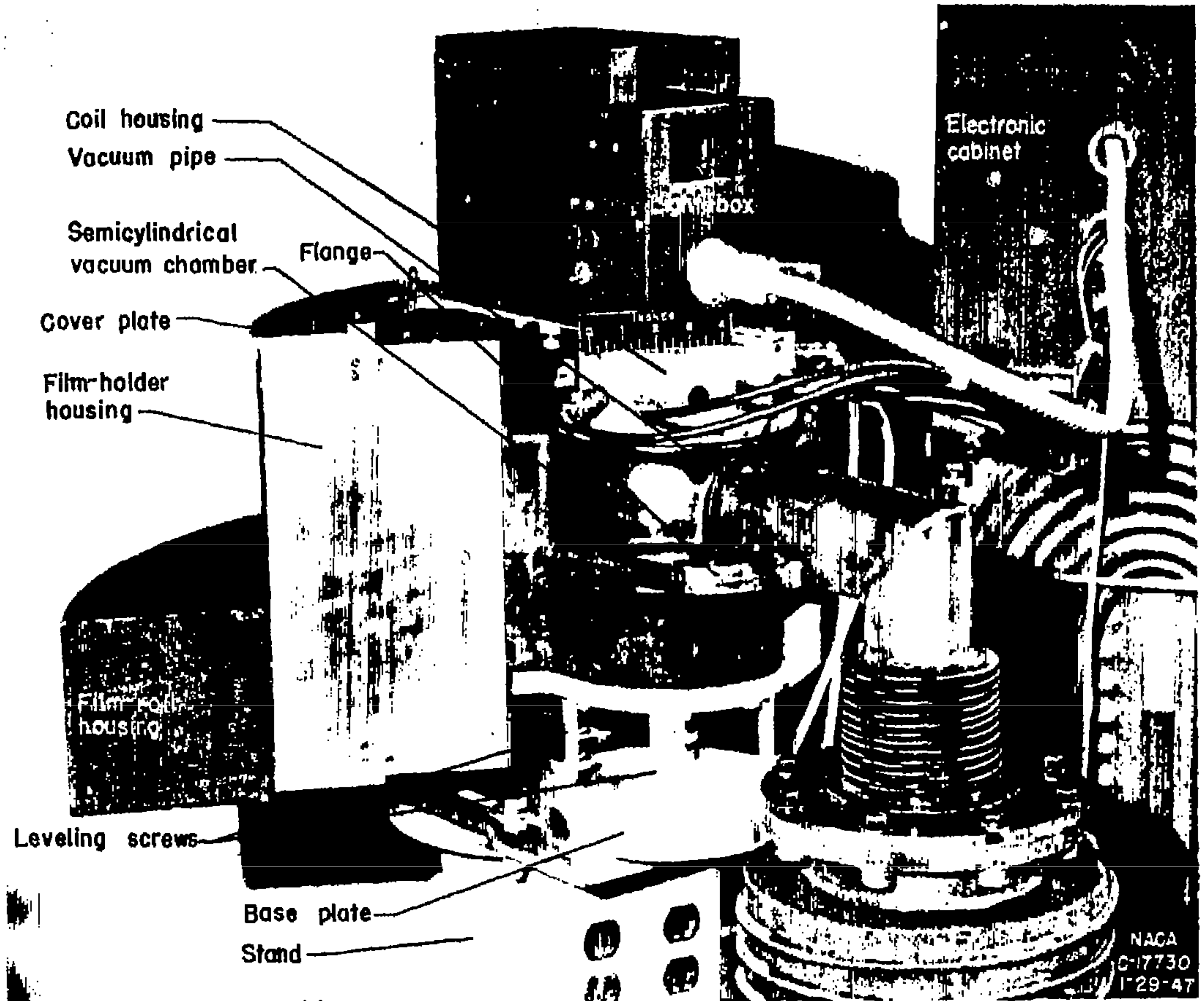

Figure 5.- Front view of ultrahigh-speed camera.

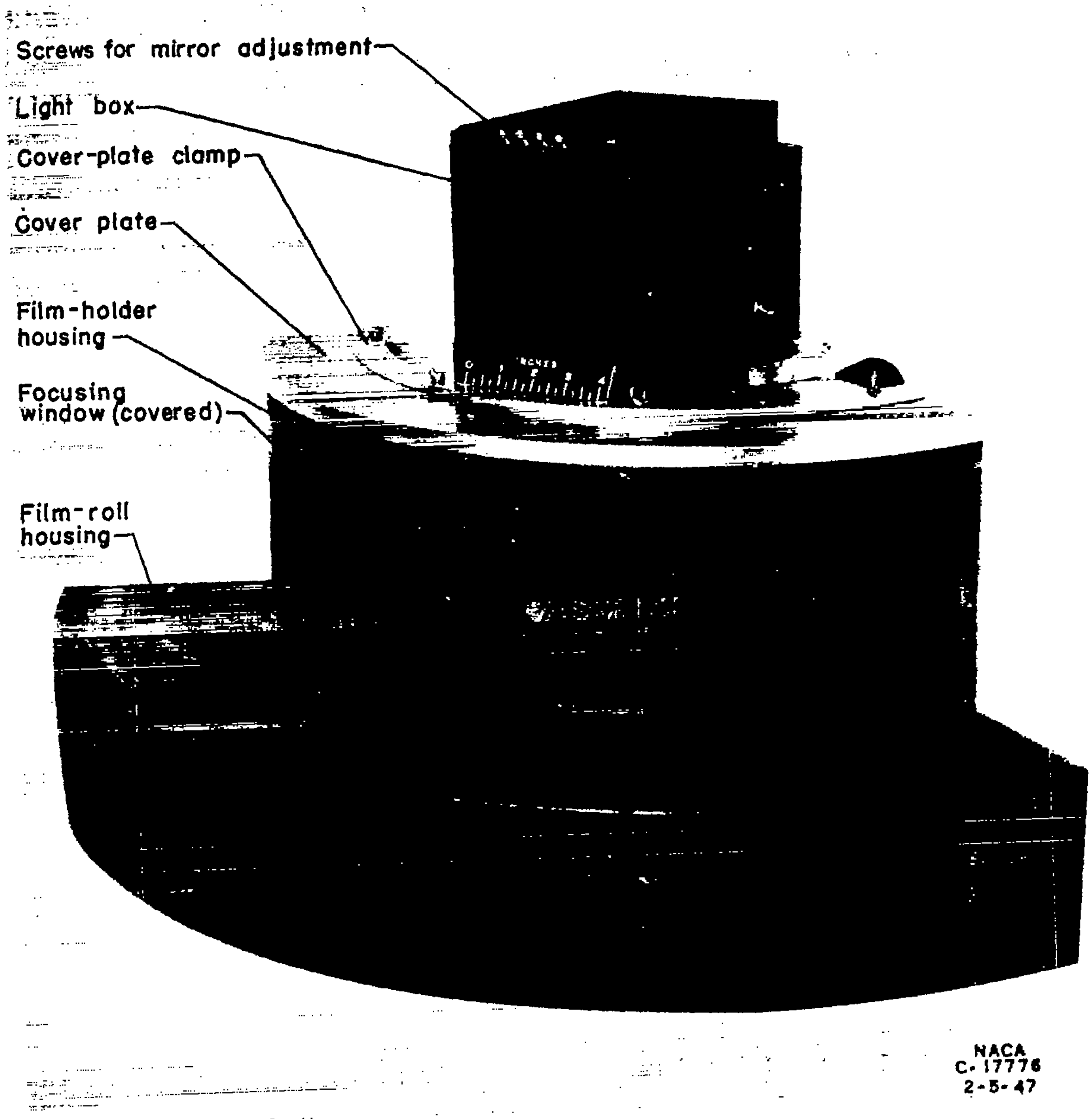

Figure 6. - Rear view of ultrahigh-speed camera.

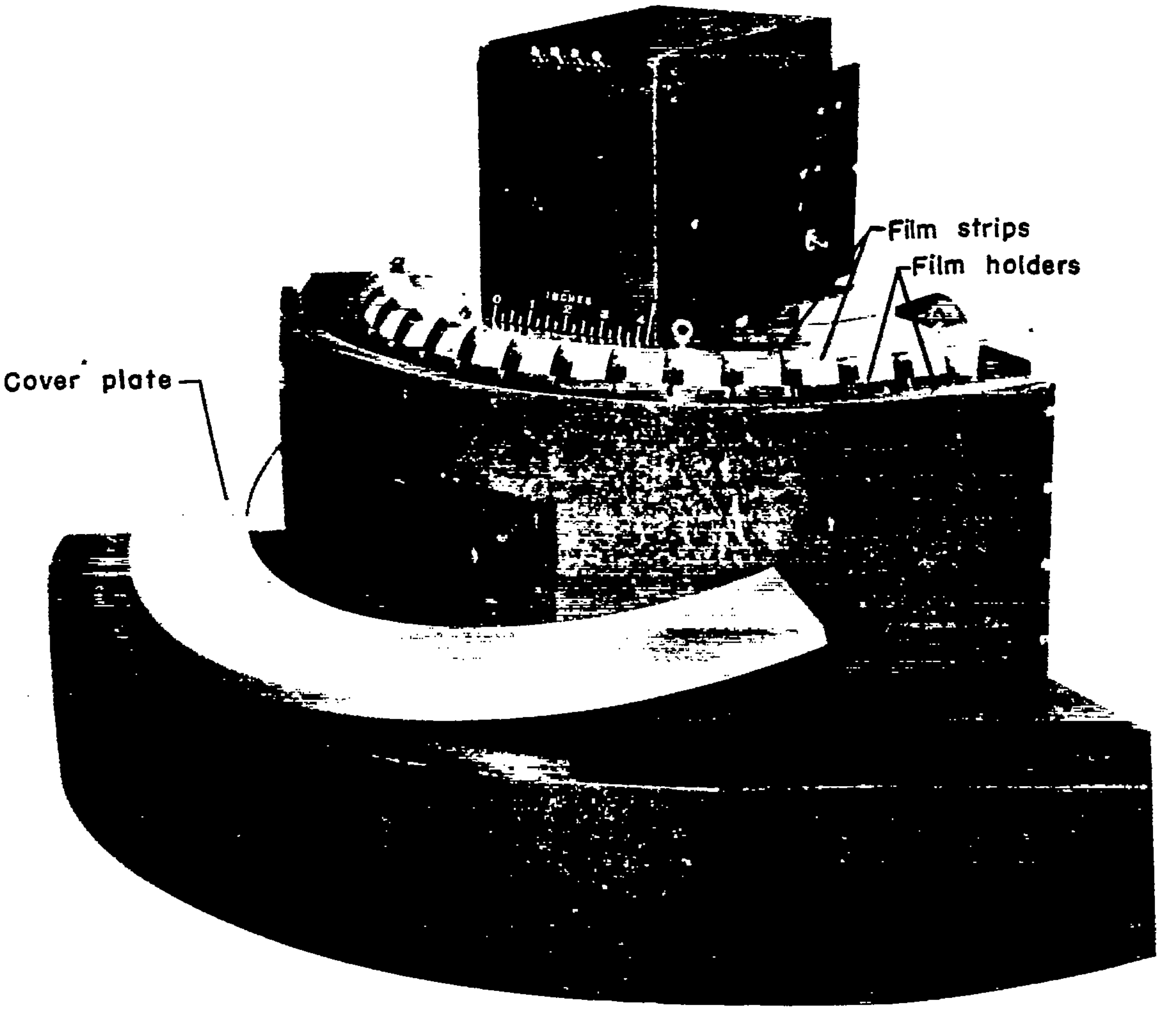

Figure 7.- Rear view of ultrahigh-speed camera with cover plate removed from film-holder housing.

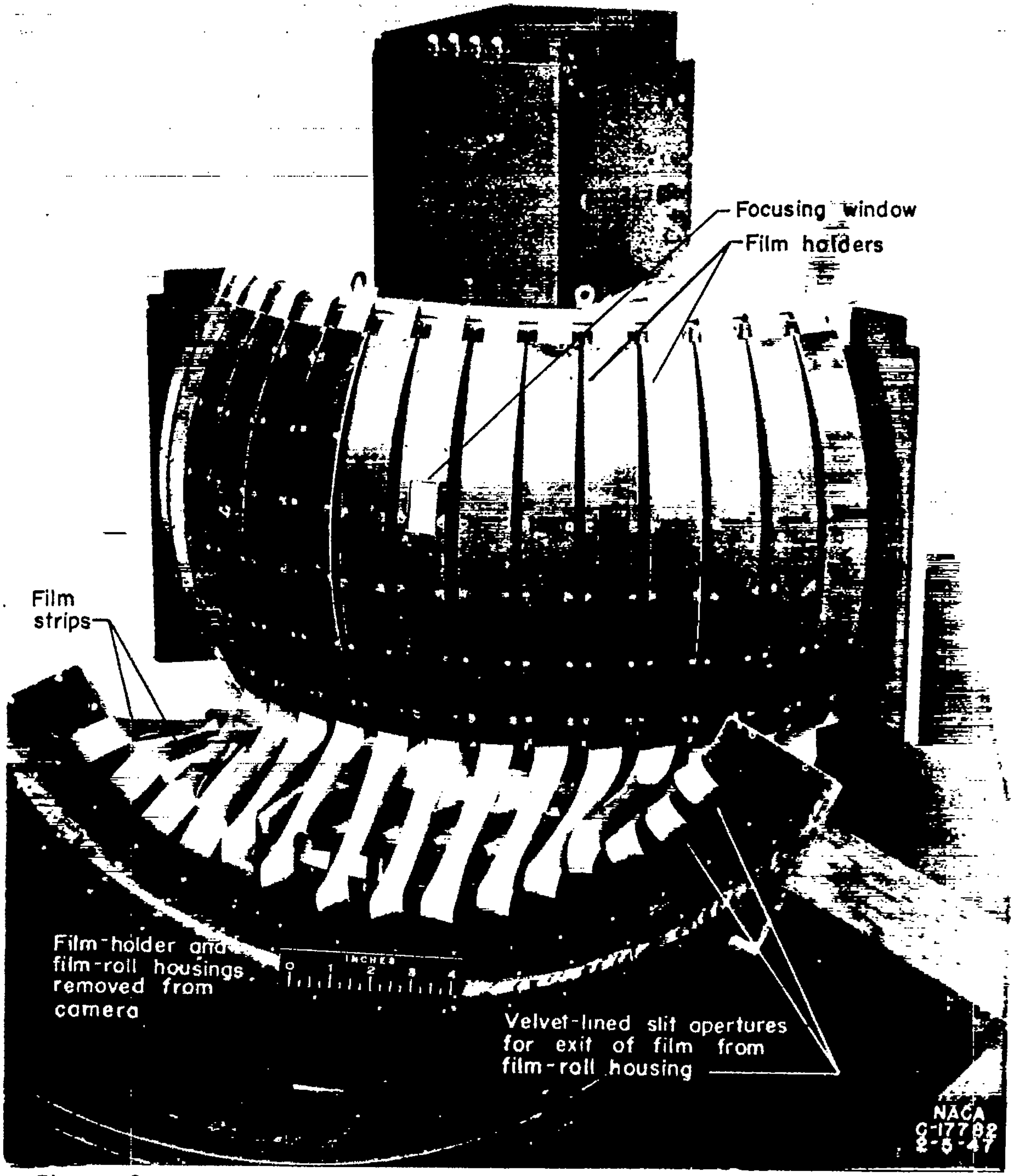

Figure 8.- View of curved film holders of ultrahigh-speed camera with housings removed.

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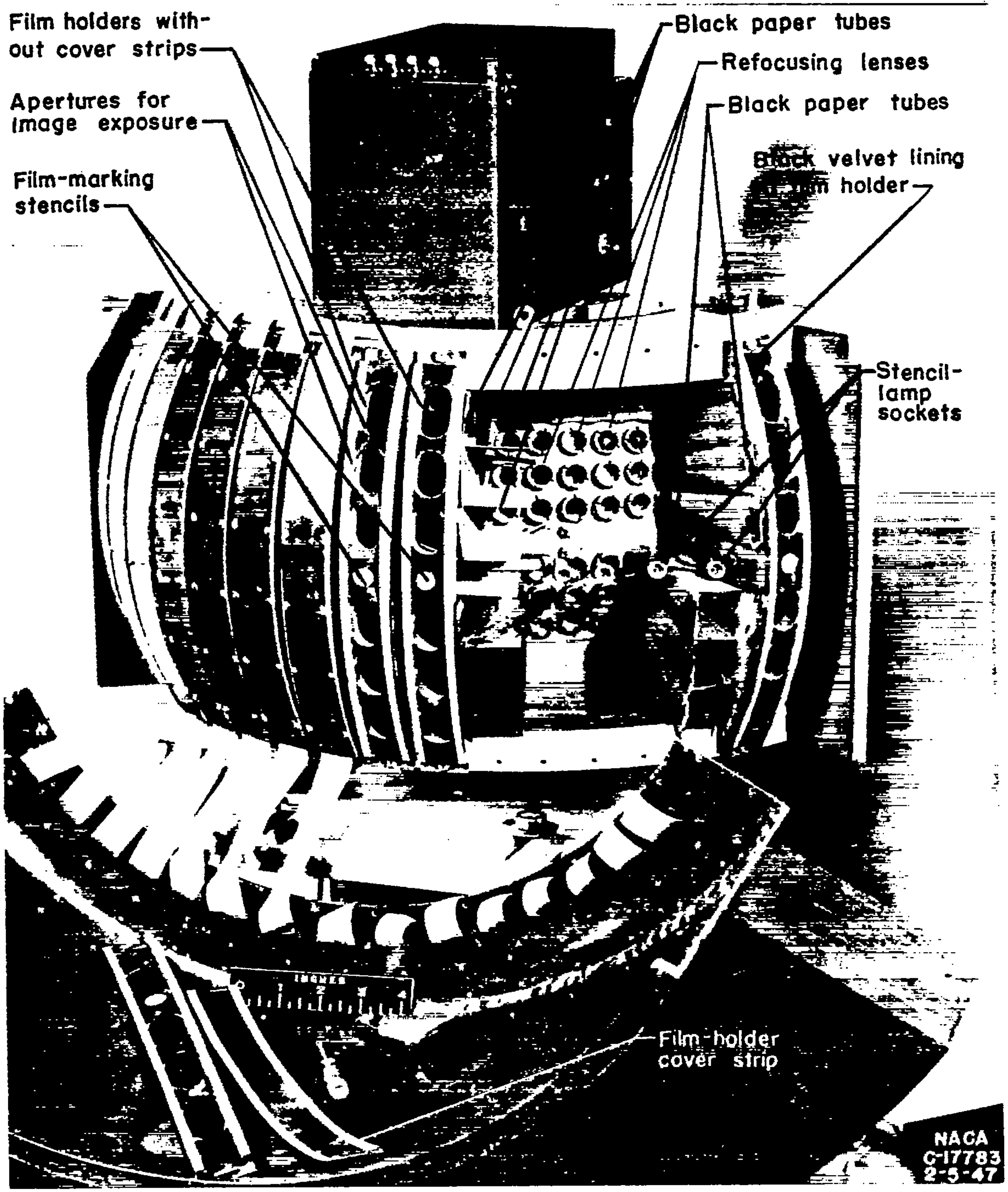

Figure 9.- Ultrahigh-speed camera partly disassembled showing details from refocusing lenses outward.

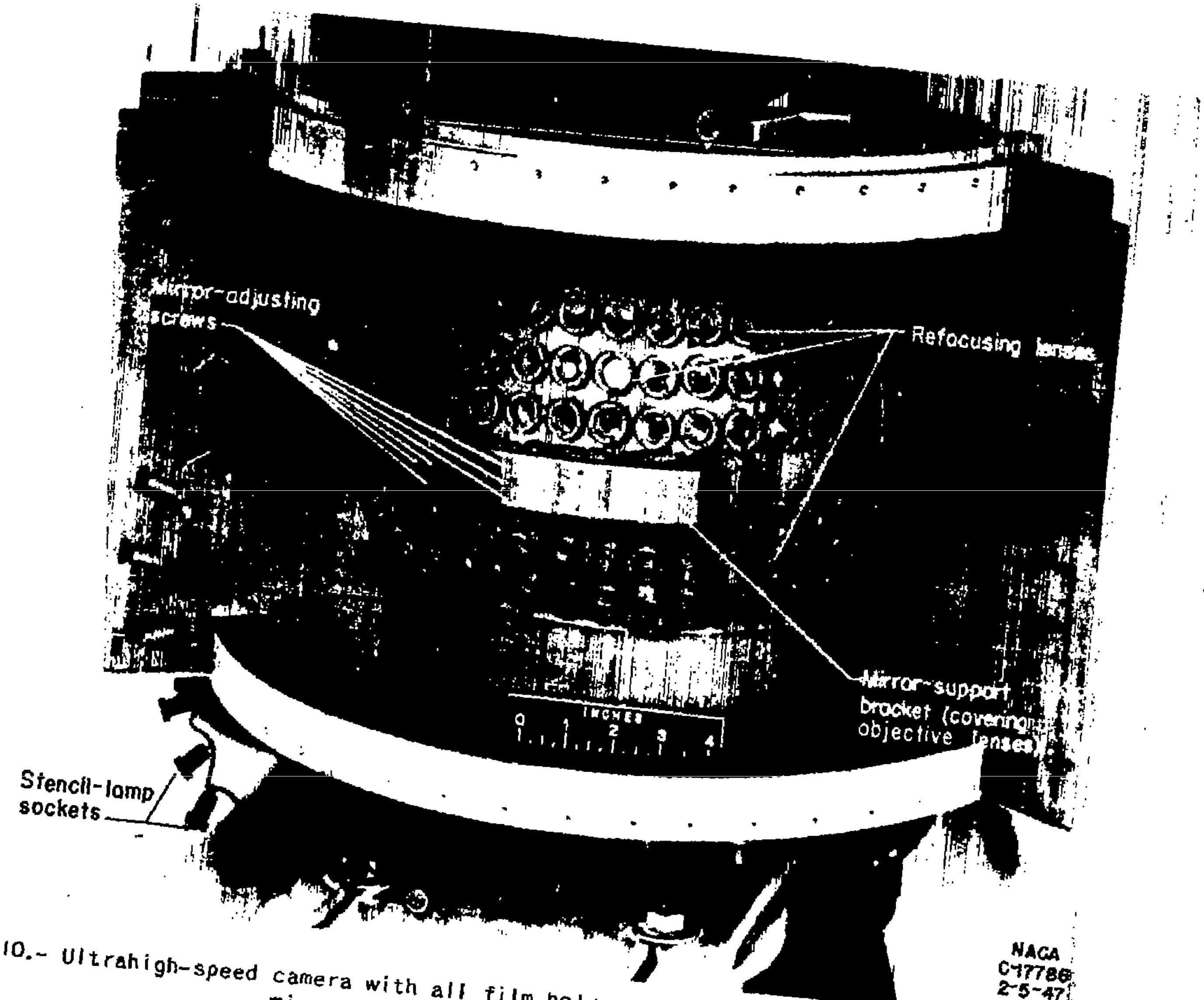

Figure 10.- Ultrahigh-speed camera with all film holders removed showing 90 refocusing lenses and mirror bracket over four objective lenses.

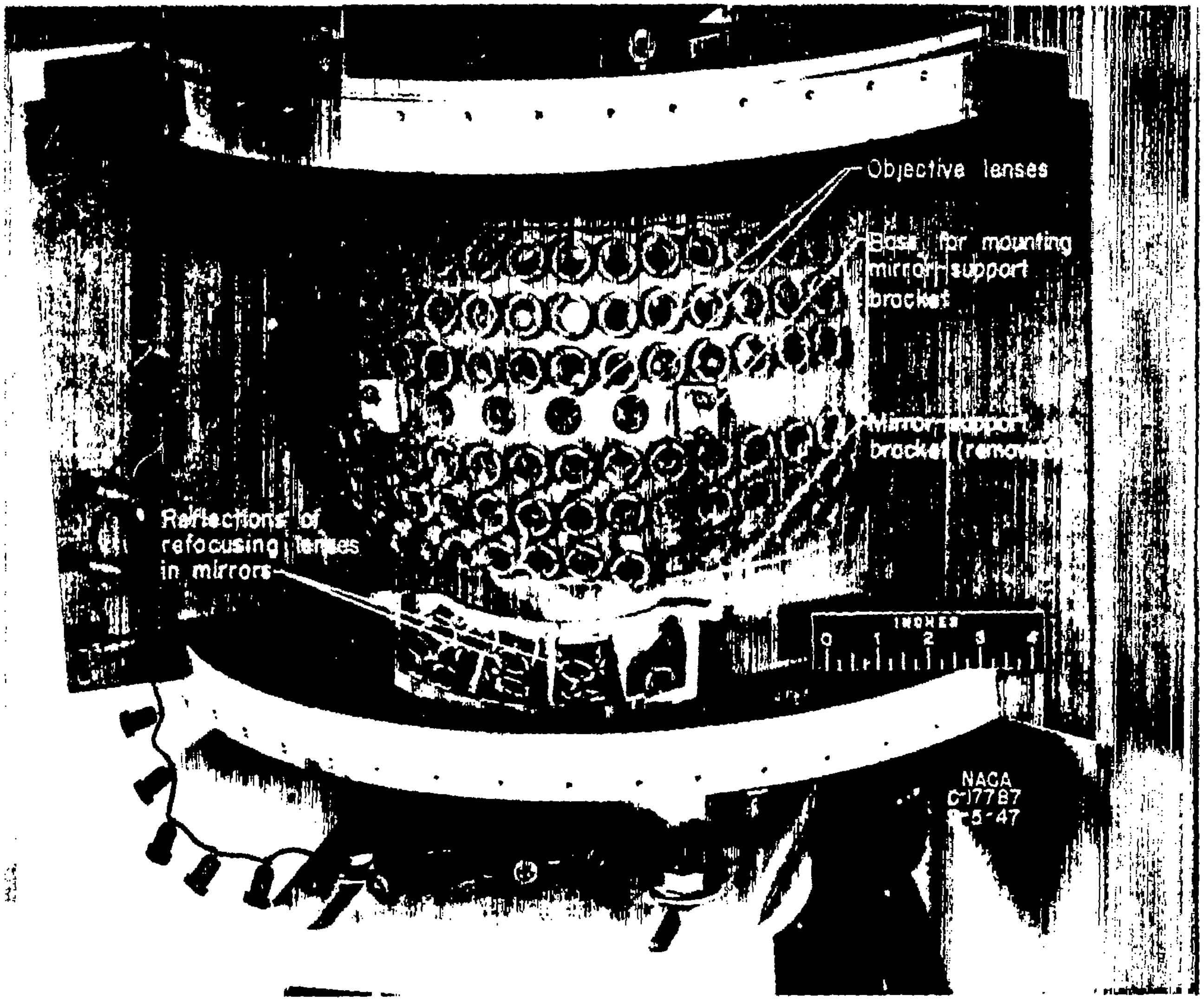

Figure 11.- View of 90 refocusing lenses and four objective lenses of ultrahigh-speed camera.

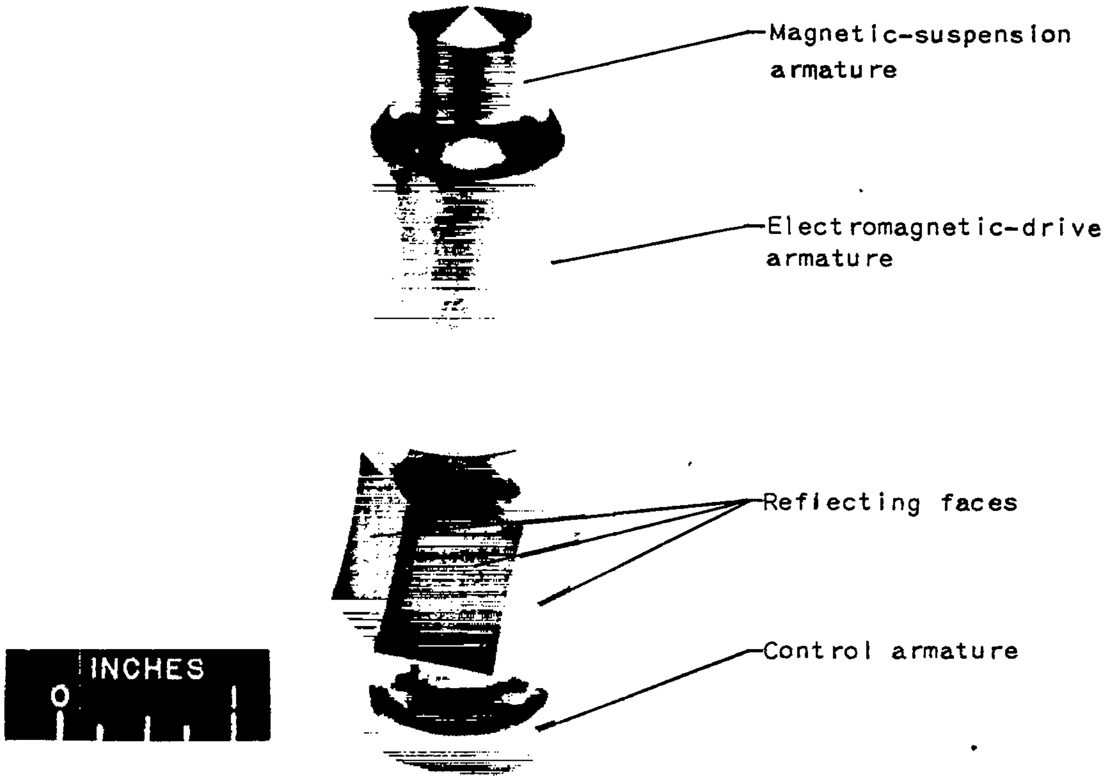

Figure 12.- Rotor used with magnetic suspension and drive in ultrahigh-speed camera.

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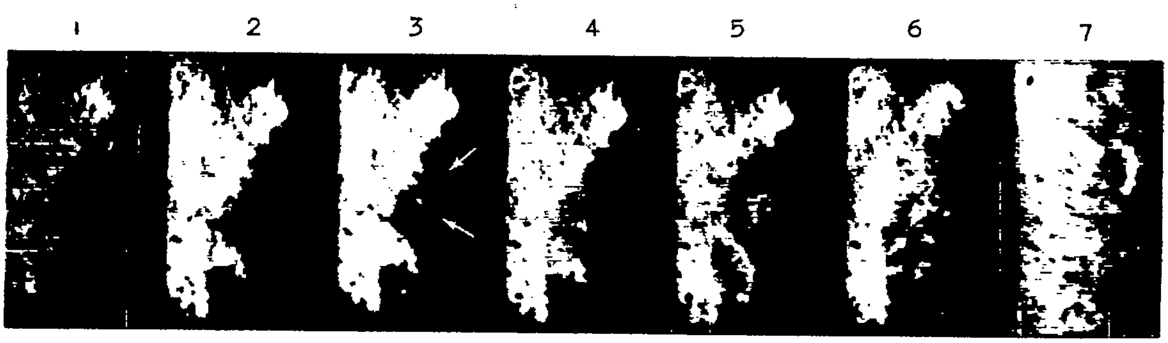

Figure 13.- Seven selected frames from sequence of knock in spark-ignition engine taken at 200,000 frames per second with ultrahigh-speed camera. (Arrows in frame 3 indicate start of knock development.)